Article Title: Deciphering long-term records of natural variability and human impact as recorded in lake sediments: a palaeolimnological puzzle

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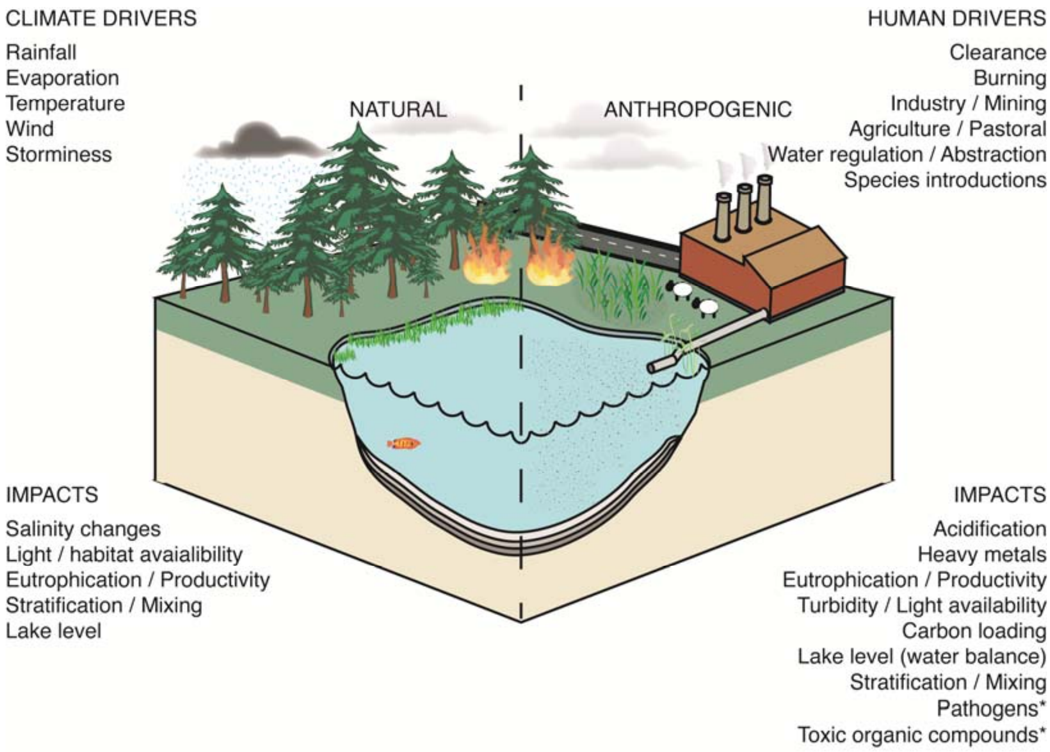
Abstract

Global aquatic ecosystems are under increasing threat from anthropogenic activity, as well as being exposed to past (and projected) climate change, however, the nature of how climate and human impacts are recorded in lake sediments is often ambiguous. Natural and anthropogenic drivers can force a similar response in lake systems, yet the ability to attribute what change recorded in lake sediments is natural, from that which is anthropogenic, is increasingly important for understanding how lake systems have, and will continue to function when subjected to multiple stressors; an issue that is particularly acute when considering management options for aquatic ecosystems. The duration and timing of human impacts on lake systems varies geographically, with some regions of the world (such as Africa and South America) having a longer legacy of human impact than others (e.g. New Zealand). A wide array of techniques (biological, chemical, physical and statistical) is available to palaeolimnologists to allow the deciphering of complex sedimentary records. Lake sediments are an important archive of how drivers have changed through time, and how these impacts manifest in lake systems. With a paucity of 'real-time' data pre-dating human impact, palaeolimnological archives offer the only insight into both natural variability (i.e. that driven by climate and intrinsic lake processes) and the impact of people. Whilst there is a need to acknowledge complexity, and temporal and spatial variability when deciphering change from sediment archives, a palaeolimnological approach is a powerful tool for better understanding and managing global aquatic resources.

Graphical/Visual Abstract and Caption



Graphical abstract: Drivers and impact: the confounding effects of people and climate on lake sediment records

INTRODUCTION

Despite only 0.013% of the Earth's water occurring in lakes (both fresh and saline), these systems are fundamentally important to the environment and biosphere and, of course, human populations in terms of the ecosystem services they provide[1]. Not only are lakes under increasing stress from anthropogenic impacts, they are also vulnerable to Earth's changing climate[2] (see Figure 1). Understanding how freshwater ecosystems change through space and time is crucial to ensuring global-scale resource sustainability at a time when humans increasingly drive environmental change. The ability to recognise environmentally transformative anthropogenic impacts on aquatic ecosystems[3], distinct from natural variability, is a key challenge in understanding the onset, and nature, of the 'anthropocene', especially as human-driven changes and impacts on the environment are time-transgressive[4] and regionally and environmentally-specific[5]. Coupled with this exists a need to understand how key Earth systems respond to tipping points caused by climatic variability and human activity[4].

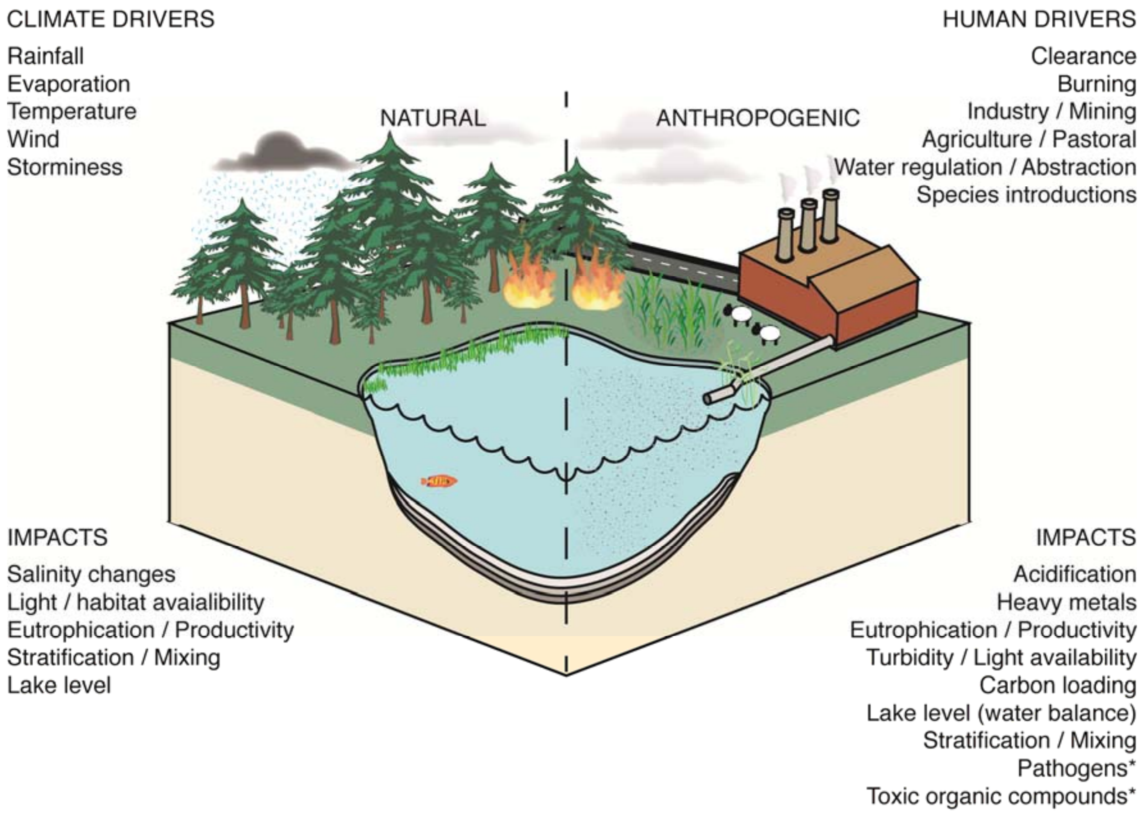


Figure 1: A summary diagram highlighting climatic and anthropogenic drivers, and the impacts they have on lake systems. It should be noted that both climate and humans can cause changes in lake systems that manifest in a similar fashion in the lake sediment archive, and that multiple lines of evidence used together are required to fully apportion the impacts of the different drivers (see Table 1 also) (*these impacts are not covered in the text).

There are increasing scientific and management concerns regarding the timing and onset of human activity, and in conjunction with changing climates (see Figure 2), how these two major drivers have interacted to modify aquatic ecosystems in the past[6, 7]. Whilst an increasing number of lake systems are monitored *in situ*, or remotely and in real-time (e.g. as part of programmes such as GloboLakes, GLEON and UKLEON)[8-10], we are largely monitoring already impacted ecosystems. Furthermore, there is a tendency to direct monitoring efforts towards aquatic systems that are deemed the most impacted or 'at risk' and such assessments are generally based on recent (past few decades) measured or anecdotal data. As a result, possible effects from pre-20th century human activities are unknown, meaning long-term records of environmental change are required to adequately validate ecosystem response to climatic and anthropogenic drivers. The use of palaeolimnology (see Box 1) often provides the only long-term evidence of change in aquatic ecosystems, be it climate- or human-driven, and is often the only available record concerning the onset and impact of human disturbance.

Despite work that extends back several decades, culminating in large scale projects such as the PAGES (Past Global Changes) initiative LIMPACS[11] (Human and Climate Interactions with Lake Ecosystems), our understanding and our ability to disentangle what are human-driven and climate-driven changes in lake systems still requires much work. Some of these issues, in part, arise from how we might define 'change' in an aquatic ecosystem. For example, whilst changes in catchment vegetation due to anthropogenic land-use change (e.g. burning) might be recorded in the sediments contained within lake ecosystems, this 'change' may not invoke a response in the aquatic ecosystem itself[12-15]. To this end, there is a difference in what can be thought of as evidence for first impact as distinct from the first impact that alters the structure and function of an aquatic ecosystem[3]. Fundamental questions still surround whether we can confidently separate the signals of stress triggered by human activity from change due to natural variation when analysing lake sediments[7] especially when these co-occur.

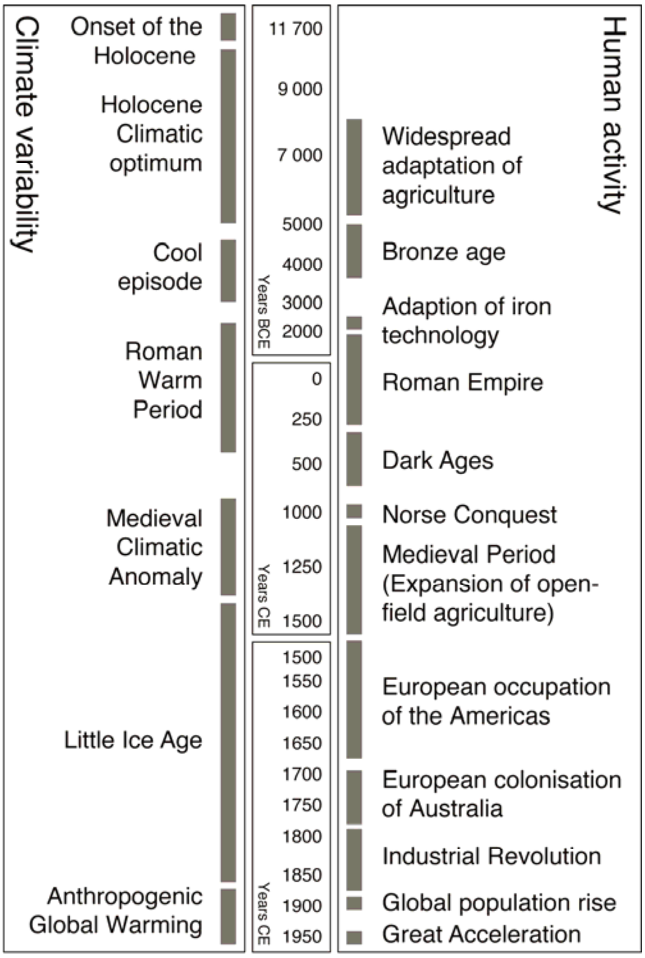


Figure 2: A generalised schematic of major climatic episodes and historical periods of population expansion.

Having the ability to apportion what is natural variability and what is anthropogenically induced allows us insight into how aquatic systems might respond under future changes, or different combinations of stressors in the future. Whilst many aquatic ecosystems have endured the impacts of climate change, their adaptive capacity has likely been compromised by the deleterious effects of direct human impacts. This knowledge can be used to underpin strategies and policies relating to water and catchment management, especially in systems where it is the legacy of combined past climate and human interactions that result in the systems that currently exist[16].

BOX 1: What is palaeolimnology? Lakes as sentinels of environmental change

The term palaeolimnology is derived from the Greek for ‘old’ (paleon), ‘lake’ (limne) and ‘study’ (logos). Sediment cores are extracted from lake systems, and the physical, chemical and biological properties of those sediments are investigated (Table 1). Such analyses require careful collection, dating and proxy measurements. **Core collection:** Coring devices have been designed to extract sediment sequences from lakes with minimal distortion[17-19]. Some are suited to recovering shallow, unconsolidated sediments[20], others for collecting deeper, compacted sediments[21, 22]. Sub-sampling strategies vary depending on the nature of the sediments; where there is no clear stratigraphy, uniform slicing is commonly undertaken (e.g. at mm/cm intervals)[17]. Where there is a clear stratigraphy (e.g. annual laminations) structural sub-sampling is preferred. **Dating:** Chronologies are often constructed for lake sediments archives using radioisotope techniques of ^{210}Pb (last c. 120 years)[23] and ^{14}C (back to c. 50,000 years)[24-26], man-made nuclides (^{137}Cs, ^{241}Am) from nuclear weapons testing (1960s) and the Chernobyl disaster (1986) and other deposits such as spheroidal carbonaceous particles [27]. **Proxy indicators:** Past conditions are inferred from one or (ideally) multiple sources of environmental information (‘proxies’) contained within a sediment core (see Table 1). Lithological analyses examine variations in colour, texture, density or particle size of the sediments[28]. A suite of mineralogical, geochemical, spectrophotometric and magnetic measurements can be made and the stable isotopic and organic matter composition determined[29]. Identification of biological remains (palaeoecology) including pollen, macrofossils (e.g. chironomids) and microfossils (e.g. diatoms) provides information on changes in catchment vegetation or lake conditions (e.g. water chemistry) at the time of their deposition[30].

		CLIMATE					HUMAN								
		Precip.		Temp.		Wind	Catchment disturbance								Atmos.
	PROXY INDICATOR	Lake level	Habitat change	Stratification	Burning	Stratification	Eutrophication	Hydrology (inc. lake level)	Burning	Vegetation	Sediment quality	Turbidity	Urban / Industry / Mining	Species introductions	Particulates (e.g. causing acidification)
Physical	MAR	■						■							
	Sedimentology	■		■		■	■	■			■	■			
	Magnetic susceptibility							■					■		■
Chemical	Synthetic compounds										■	■	■		
	Stable isotopes	■						■		■					
	Geochemistry			■	■	■	■	■			■		■		■
	Sedimentary DNA		■							■				■	
Biological	Diatoms	■	■	■		■	■					■			■
	Pollen	■	■	■		■	■		■	■				■	
	Chironomids	■	■	■		■	■						■		
	Pigments		■	■		■	■								
	Cladocerans		■											■	
	Plant macrofossils	■	■		■					■				■	
	Charcoal				■				■	■					

Table 1: A summary of the various (but not exhaustive) list of proxy indicators referred to in the text. The filled boxes highlight what each proxy can be used to infer (i.e. the different drivers of change in an aquatic system). It should be noted that many proxies can be used to infer a large number of drivers, both climatic and anthropogenic in origin. There are very few proxy indicators that are unambiguous in terms of drivers, however the use of two or more of these indicators (multiproxy) from lake sediment archives can increase our certainty as to the cause of change (Precip. = Precipitation, Temp. = Temperature, Atmos. = Atmospheric).

Natural variability in lakes

Palaeolimnological studies allow scientists to place the current condition of a lake system into an historical context. Natural variability is generally defined as the variation in an ecosystem in the absence of human impact, and is often referred to as the 'baseline' or 'reference' condition[16]. The natural variability observed in lake systems, and as recorded in a lake's sediment archive, is driven by external (i.e. climate) and internal factors (i.e. lake development through time in relation to natural succession). One of the major challenges is in identifying what change is inherently natural, what lies outside natural variability, and therefore what may constitute evidence for 'first human impact' in lake sediment archives. The relative ease of identifying natural versus anthropogenically forced change will vary dependent on where you are in the world, and the type of lake (i.e. deep vs shallow)[3]. Some regions have a far longer human-environment history than others, and in some areas technologies and associated impacts have evolved gradually through time (e.g. Europe) compared to parts of the world where there have been more recent step changes in human activity and landscape impact (e.g. New Zealand).

The majority of aquatic systems across the globe have now experienced some form of human impact and this has compromised our ability to make an objective assessment on the degree of degradation. Such assessment a system necessitates an in-depth understanding of how lake systems have behaved in terms of ecological pattern and function in the absence of major human modification. The temporal perspective (see Box 2) plays an important role in defining 'reference conditions'[31] in aquatic systems. For example, land and water managers are often interested in short time periods, whereby the influence of most major climate fluctuations (e.g. glaciations) is not exerting an influence. However this has led to a date of 1850 CE (Common Era) being used as a suitable date against which to assess impacts of anthropogenic activity on lake systems[32, 33] as this date is perceived to represents a period prior to major industrialization and agricultural intensification (in the Northern Hemisphere). Yet many palaeolimnological case studies offer a longer time perspective on periods of major agricultural fluctuations, and suggest that intensified agricultural impacts began as early as 6000 years before present (e.g. in Denmark)[34].

Human-lake interactions

People and societies have long interacted with the landscapes they inhabit, and throughout history humans have preferentially settled alongside sources of freshwater to satisfy their basic needs for water, food, hygiene and transportation[35]. As a consequence, both inland and coastal lake systems have been disproportionately affected, and exploited, by humans since their arrival in a particular region. Anthropogenic pressures on aquatic systems can take many forms, and can be highly variable both temporally and spatially in response to, for example, the advent and development of new technologies. Anthropogenic pressures within lake catchments can range from clearance and/or modification of vegetation cover, which may affect sediment loading to lakes (and changes in the burial of carbon)[36] through increased erosion, and the delivery of nutrients to the system (which may also be exacerbated if the catchment is converted to predominantly agriculture). Furthermore, a change in catchment activity can alter the hydrology of a lake (including diversions of inflows and outflows) as can local water abstraction leading to changes in groundwater interactions[37, 38]. Other catchment modifications, such as urbanisation and industrialisation may lead to the input of pollutants, both directly (e.g. heavy metals), and indirectly from atmospheric deposition (e.g. nitrogen). People often introduce non-native species to lake systems, either purposefully for commercial gain (e.g. the introduction of the Nile Perch in African rift lakes[39]) or accidentally through transport networks (e.g. zebra mussel in Europe and North America[40]). These pressures often lead to significant changes in the dynamics and functioning of the lakes and to modifications of the structure of biotic communities within.

The impact of multiple stressors

Aquatic ecosystems are therefore impacted by a complex mix of stressors[41, 42]. These stressors occur in biotic (e.g. nutrient loading) and abiotic (e.g. water abstraction) forms, and can occur naturally or be anthropogenic in origin[43]. Whatever the origin of the driver, the stressors have consequences on the ecosystems in question[41]. Furthermore, these stressors rarely occur in isolation, and are a result of a multitude of drivers, with complex interactions which vary both spatially and temporally[43] (see Figure 3). The energy-mass flux framework (E*m* flux) combines a limnological and palaeolimnological process-oriented approach to understand present functioning and future trajectories of systems exposed to multiple stressors[43]. This framework centres on the premise that climate variability is the main regulator of aquatic response through time, with energy being transferred to a system either directly (e.g. heat) or indirectly (as a result of changes within the lake catchment). Similarly, mass can be transferred to an aquatic system directly (e.g. via precipitation or solutes from the atmosphere) and indirectly (via solutes or water from the catchment). The palaeolimnological approach serves to indicate both the specific impacts of drivers alongside the complex interactions, driven not only by the interplay of the stressors, but also characteristics intrinsic to the individual lake (e.g. catchment size, lake morphometry and depth). The framework clearly indicates that where human activities dominate within a lake catchment, the input of mass becomes the dominant driver, overriding the direct effects of energy[43]. Thus, there is increasing evidence that the negative impacts on lake ecosystems as a result of multiple, interacting stressors increases the sensitivity of the lake to any given future stressor[41, 42, 44].

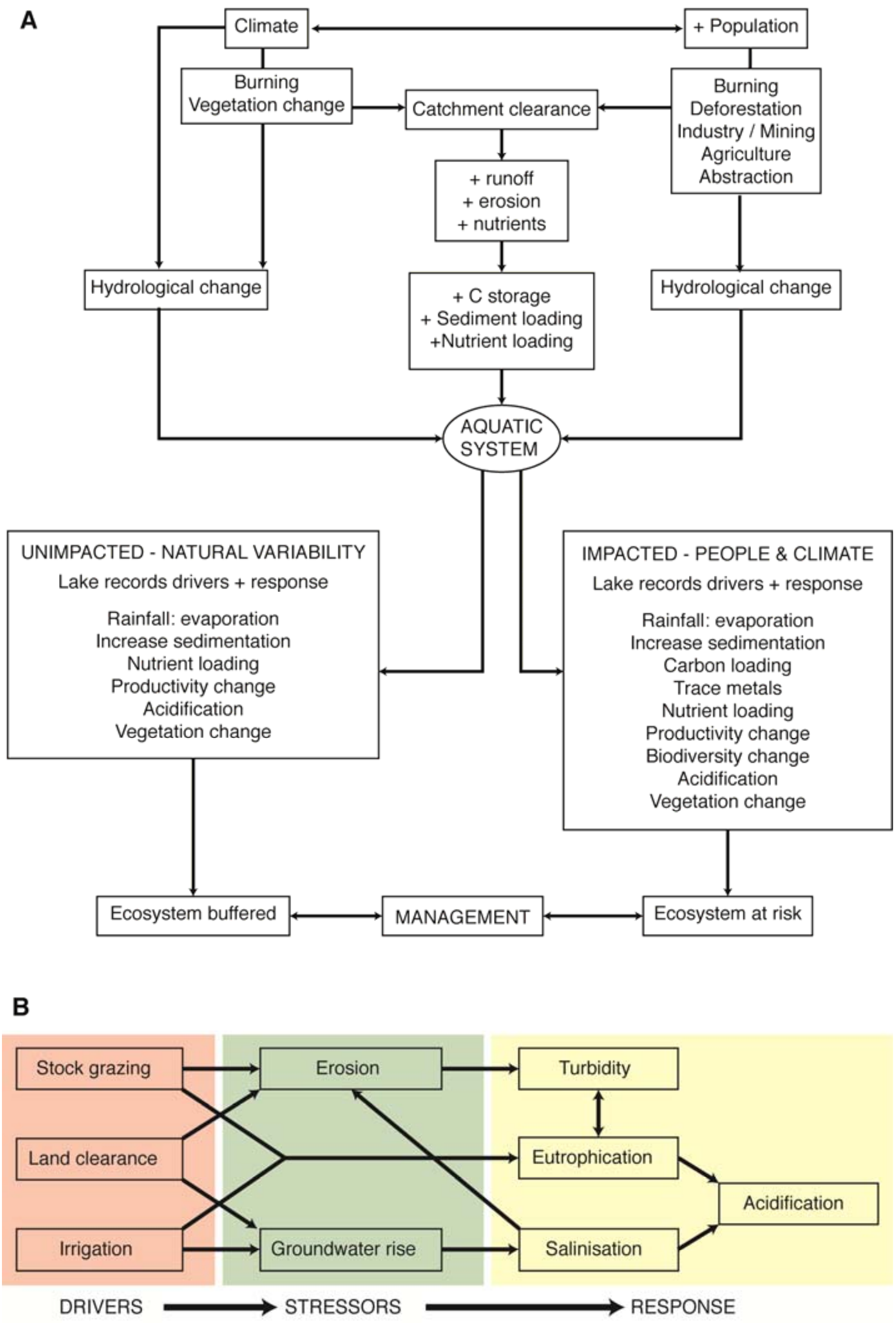


Figure 3: (A) a flow diagram summarising the complex interactions of drivers (both climatic and anthropogenic) that affect aquatic systems, and the associated impacts that may be recorded in the lake sediment archive, and how this may differ between unimpacted and impacted lake catchments, as the legacy of impacts often alters the response of an aquatic ecosystem to future stressors[16]. (B) A flow diagram highlighting the complex interactions of anthropogenic drivers and their impacts on water quality as recognised in the palaeolimnological records of the Murray-Darling Basin wetlands[45]. These wetlands have been subjected to multiple stressors, often coincidentally, and is attributed to the causal co-variation between several anthropogenic drivers and stressors in the Murray-Darling Basin[45] [Redrawn and adapted from Gell et a. (2007)].

Temporal resolution and ecological scaling

The temporal resolution of the proxy record is a function of the sedimentation rate, the mixing rate and the sampling interval (see Box 1). Depending on these factors, which vary considerably among systems due to allochthonous and autochthonous productivity, catchment disturbance and sediment focussing, a mm-thick sediment sample may represent seasonal planktonic inputs[46] or a 1-cm sample c. 25 years, and hence longer-term processes. Bioturbation is rarely a substantial problem in small lakes (due to anoxia and low faunal densities) but wind-driven resuspension can cause mixing of unconsolidated sediments, particularly in shallow water. This difference between littoral and profundal zones has considerable implications for assessing whole-lake response to disturbance, particularly as the littoral zone is often the location of maximum production and biodiversity[47]. The implications of sediment temporal resolution for understanding whole-lake ecological response to disturbance are covered in detail elsewhere[48]. It is important that the ecological interpretation of the sediment sample/assemblage is matched with the processes that are most relevant at the temporal resolution observed[49, 50]. Most lakes have strong intra-annual variability associated with light and production cycles, but these signals are rarely preserved in the sediment record (with the exception of annually-laminated sediments; below). As well as considering ecological scaling, it is important that the sample resolution is considered when comparing recent anthropogenic-driven change with background, 'natural' variability. Change in temporally-smoothed stratigraphies (due to sampling interval or mixing) can appear muted when compared to apparent rapid change in recent sediments with higher sedimentation rates.

Box 2 figure: Images of cleaned freeze cores illustrating the range of temporal resolution in lake sediments. Far left: annually laminated sediment from Nylandssjön, Sweden, covering c. 20 years. Left: irregularly laminated sediment from SS86, SW Greenland covering c. 1500 years (photo credits: Ingemar Renberg).

Implications for management

Long-term palaeolimnological records, in combination with sediment-derived reference conditions can be used to enable land and water managers to set limits of acceptable change that are feasible to maintain[51]. For example, analysis of a suite of lakes in the middle and lower reaches of the Yangtze River, China, indicates that the system exhibited large fluctuations in ecological community structure over the last 200 years[52]. This variability was intrinsically linked to a number of factors, including internal lake forcing, the efficiency of the large catchment in delivering nutrients to the river, and particularly water management actions that altered the interaction of the lakes with the main river system[52, 53].

There is often widespread expectation that the purpose of lake management is to improve, or restore, an ecosystem to a pristine condition, commonly perceived as that which existed prior to known human impact. In the case of the Ramsar Convention, established in 1971 to protect the world's most significant wetlands, for example, it is anticipated that management targets should retain the recognised condition of the system under question[53]. However, without detailed knowledge of long-term natural variability and the full history of human impacts on aquatic ecosystems, such goals may be erroneously set. These targets often ignore the inherent variability of lakes in response to changing hydroclimate and the directional change that lakes undergo through hydroseral evolution and ongoing infilling. Further, they often overlook the unreliable nature of human memory as a means of establishing past conditions of a wetland[54]. The availability of continuous archives of lake change available in lake sediments provides a means of contextualising the modern state and to inform waterway managers of the need for, and direction of, management interventions. Despite this, long term records of change are rarely used as a resource in wetland management decisions. Palaeoecological evidence has demonstrated several examples where descriptions of "natural" biotic communities made at the time of Ramsar listing were unrepresentative and unhelpful to the long term management of many systems[53]. The integration of palaeo evidence with more recent evidence for change not only avoids the mishaps of a narrowly recent view, but better identifies the trajectories of change and the influence of any cyclical factors with long return periods. The adoption of a longer term perspective has the capacity to open up options for management to make a stronger, more targeted case for intervention.

PEOPLE AND CLIMATE: THE PALAEOLIMNOLOGICAL INDICATORS

Over millennial timescales, variations in climate have been the dominant driver of change in aquatic systems, but the overriding signal now is the impact of people, and the effects of pollution and land use change[41, 43]. The effects of climate change are often more apparent in lake systems that are remote from major centres of human populations such as the arctic and in alpine regions[55, 56]. However, there is an increasing body of evidence that suggests that even these remote systems are no longer immune from human impacts, with lake systems in Greenland and the mountain lakes of the Northwest USA showing evidence of nutrient enrichment as a result of the atmospheric deposition of nitrogen[57-60]. Transboundary pollution is not a new phenomenon, with the earliest example being that of the acidification of remote eastern North American and northwest European lakes several decades ago[61].

Over longer-timescales it can be difficult to truly quantify an unambiguous anthropogenic driver of change in aquatic ecosystems, especially if only a single line of evidence is used. This is largely a result of common responses of lake systems to both human impact and natural succession and/or climate changes. For example, increases in productivity can result from eutrophication or a warming climate which may prolong the growing season, alter the stratification/mixing regime of a lake, or enhance catchment and in-lake nutrient cycling. Additionally, lake waters may undergo changes in pH due to catchment development following deglaciation (e.g. soil development, change of catchment vegetation[62]).

One way to separate human drivers from that of natural climate or environmental change is to extend the lake sediment record back beyond the point of first human arrival (assuming this is known) and identify a particular system's natural, pre-human impact, variability. It has been argued that humans, have exerted influence on the environment for over 2 million years[63], though given relative population sizes, in conjunction with primitive technologies, it is unlikely that such early hominids were the dominant driver of environmental change until more recently. The timing and duration of human activity varies globally, and largely reflects agricultural, technological and cultural advances at the time of initial human arrival in various regions. For example, in Australia whilst long-term impacts of people through the use of fire on landscapes have been proposed, there is little evidence for the impact of the first Australians on lake ecosystems. While they are known to have extracted resources, burned emergent plants and impounded waterways, there is no clear evidence of wetland change until that of early European settlers from the late 19th Century onwards[64]. Owing to the arrival of a technology-rich society, the quite rapid increase in human population, and the introduction and proliferation of intensive grazing soon after European settlement, the impact on lake systems was substantial and abrupt. Almost all palaeolimnological investigations across the Australian continent show considerable change in state over the last two centuries, many within decades of the imposition of modern agricultural practises. While direct eutrophication is evident in areas of dense populations[65] the recent stressors on lakes also include hydrological change, abstraction of water volume for human use, salinisation, increased turbidity and sediment infilling. These substantive changes in aquatic ecosystems occur at the same time as records of hydrological balance from Australian crater lakes, and attest to substantial climate change over long term, and even recent, periods, although many lakes in larger catchments appear to have been somewhat unresponsive to this change.

In the following sections we review some of the common indicators of change preserved in lake sediments that can inform us about human and climatic changes to lake and catchment environments

Fire, vegetation and landscape change

Many pollen records provide evidence for changes in terrestrial vegetation on account of human activities and, more rarely, changes in the aquatic system itself. The main indicators of human presence are often the appearance of exotic plants that are either invasive (e.g. *Echium* in Australia) or have been deliberately introduced (such as *Eucalyptus* and *Casuarina* in the northern hemisphere and *Pinus* in the south). Fire is a mechanism that can drive rapid and dramatic vegetation change, and anthropogenic fire has been a factor in shaping plant communities through human prehistory especially in North and South America. In other regions such as Africa, Europe, or western Asia, pre-agricultural anthropogenic impacts on vegetation and fire regimes are less evident, and the presence of charcoal remains are used to infer a longer-term presence of humans in those areas[12, 66].

Pollen records in the Mesoamerican region (central Mexico to southern Panama) have been widely studied, given the long history of human occupation (ancient Mayan civilization). Periods of intensive agricultural activities are clearly seen in the pollen records, the first indication usually being an increase of maize and other disturbance indicators, such as Amaranthacea grains in Mesoamerica[67]. The increase in pollen indicative of human occupation is often concomitant with a decrease in native tropical forest taxa[68]. Pollen records from Lake Sauce (western Amazonia) indicated the occurrence of maize microfossils showing indisputable evidence of human presence[15]. Maize pollen occurred intermittently prior to c. 3380 calibrated years before present (cal. yr BP) becoming a regular component of the record between 3200 and 700 cal. yr BP. Maize agriculture appears to have been abandoned at this site long before the decline of populations associated with European arrival in the Americas. The record also suggested that fires in western Amazonia were a frequent component of the landscape for the last 6900 years and were mainly promoted by human actions. In South America, human impact during the Holocene is inferred from the increased periodicity of fire, shown by charcoal remains in sediments from lakes in south-central Chile and Patagonia. Aboriginal populations from the pre-Hispanic period may have generated extensive clearings and agricultural fields, as shown by postglacial to Holocene pollen records from the Araucanian region. Following the decline of indigenous populations brought about by the Spanish settlers, *Nothofagus* forests appear to have reinvaded open areas in southern South America. The dominance of deciduous *Nothofagus* forests over evergreen trees has been attributed to the frequent disruption of succession presumably by fire since the prehistoric period[14].

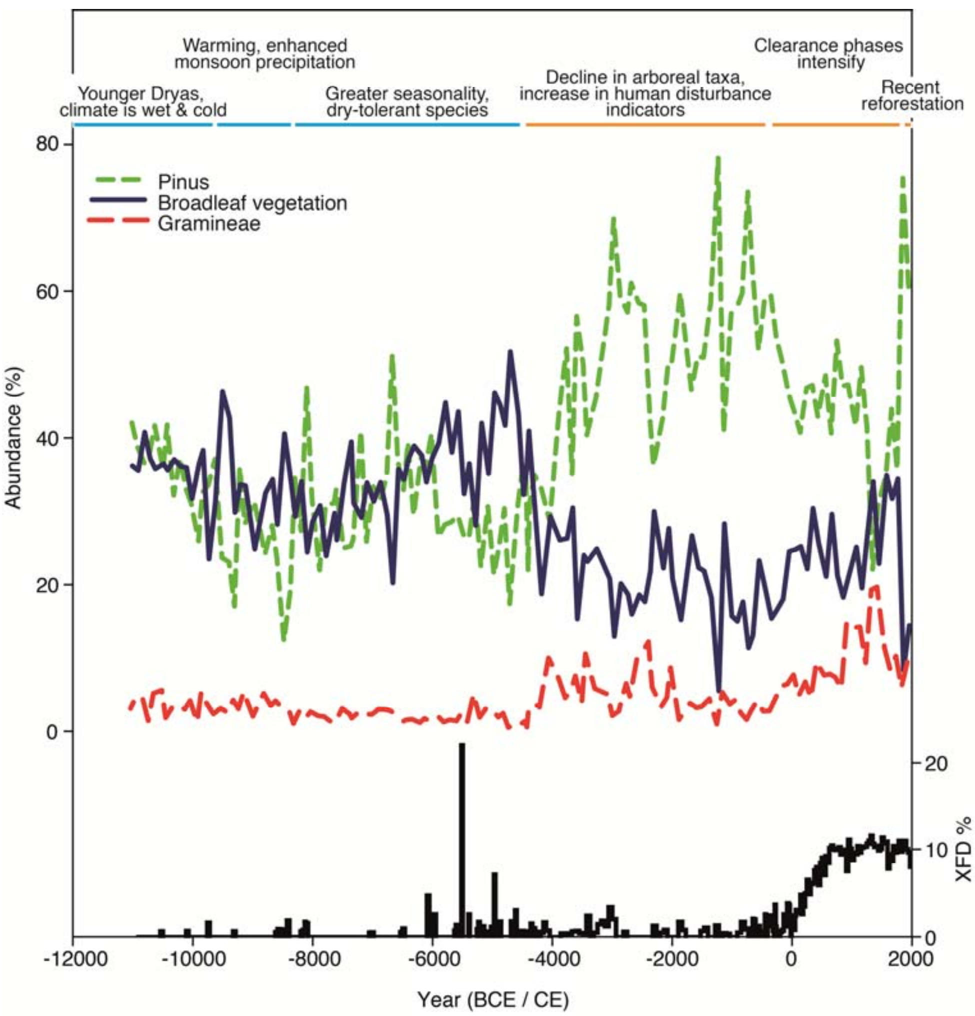


Figure 4: The pollen record from Lake Erhai, China, attests to the long-term role of climate and anthropogenic impacts in shaping the response of catchment vegetation[69]. The c. 13,000-year record suggests climate was the dominant driver of change early in the lake's history, with a gradually warming and drying climate (following the Younger Dryas) driving changes in the vegetation composition, promoting the growth of broadleaf trees. The marked decline in broadleaf vegetation, concomitant with the increase in pine and grass pollen provides the first evidence of human impact c. 6000 cal. yr BP. The persistent increase of secondary pine forest indicates that human impacts in the catchment were a result of a sustained period of shifting agriculture. Catchment modification, linked to intensified agriculture and urbanisation, increased c. 2000 cal. yr BP, as evidenced by an increase in the erosion indicator (XfD%). A sharp increase in broadleaf taxa towards the top of the record is attributed to a catchment management, and a recent phase of reforestation (c. last 25 years).[69]

In China, a 13,000-year pollen record from Lake Erhai was used to understand the relative roles of climate and human impact on the lake and its catchment (see Figure 4)[69]. The first 7,000 years of the Lake Erhai record suggest a catchment that was responsive to changes in climate, with indicators of colder and wetter conditions during the Younger Dryas (c. 11,000 yr BP). Following this, the expansion of *Tsuga* and evergreen broadleaf trees attest to a warming of the climate, and an enhanced summer monsoon. The region around the lake continued to dry, from c. 10,000 years and there was a greater seasonality in rainfall. This trend was abruptly halted c. 6000 years ago, when a marked decline in broadleaf vegetation was observed in the Lake Erhai record, concomitant with indicators of disturbance (such as an increase in grasses). This change provided an indication of first human impact in the region. The rapid expansion of pine forest, in conjunction with archaeological evidence supporting the notion of greater migration to the region, suggested a shift in agricultural practices, with successive clearance and intensification of agriculture and expansion of urbanisation. This trend continued through the last century, with a change observed only very recently in response to a phase of catchment reforestation in the last 2 decades[69].

Soil erosion and sedimentation rates

The accumulation of sediments in a lake basin over millennial timescales is influenced by climatic variation, which alters the relationship between geology, vegetation, geomorphology and soil, and in turn influences the stability of lake catchments, and their sensitivity to erosion. Changes in sedimentation rates are driven by anthropogenic modification of catchments, including vegetation clearance, burning, agricultural and industrial expansion. Fluctuations in soil erosion rates are often recorded in lake archives as variations in sediment accumulation rates (SAR) [70, 71] or in geochemical profiles[72, 73]. Long-term records of SAR during the Holocene indicate that accumulation rates generally exhibit a gradual decline through the early- to mid-Holocene as soils began to stabilise as a result of increasing vegetation cover[70]. Any short-lived perturbations in this pattern are most likely attributed to anthropogenic triggers (see Figure 5). Often the abruptness and magnitude of a rise in SAR is a good indicator of the origin of the disturbance: a gradual change in SAR would be expected in response to climatically-driven forest expansion or glacier movement, while 10- to 30-fold increases after clearance for cultivation have often been recorded[71, 74-76]. It is also possible to quantify the relative input of terrestrial vs aquatic matter to a lake via the analysis of the carbon to nitrogen ratio (C/N) in the sediment (a predominantly aquatic signature is <10, a ratio >10 is indicative of a stronger terrestrial input), thus allowing us to better understand the origin of the changes in SAR[77]. Enhanced soil erosion, triggered by human activity, may also modify the climate-erosion relationship –some systems may become more sensitive to climate-driven changes[44], others appear to be desensitised to climate-driven effects[78]. In some catchments, disturbance increases the apparent flood-frequency by increasing the sensitivity of a given catchment area to storm-triggered erosion[79, 80], and often manifests in the sediment record as an anomalous increase in the thickness vs. grainsize relationship[80, 81] (see Figure 6).

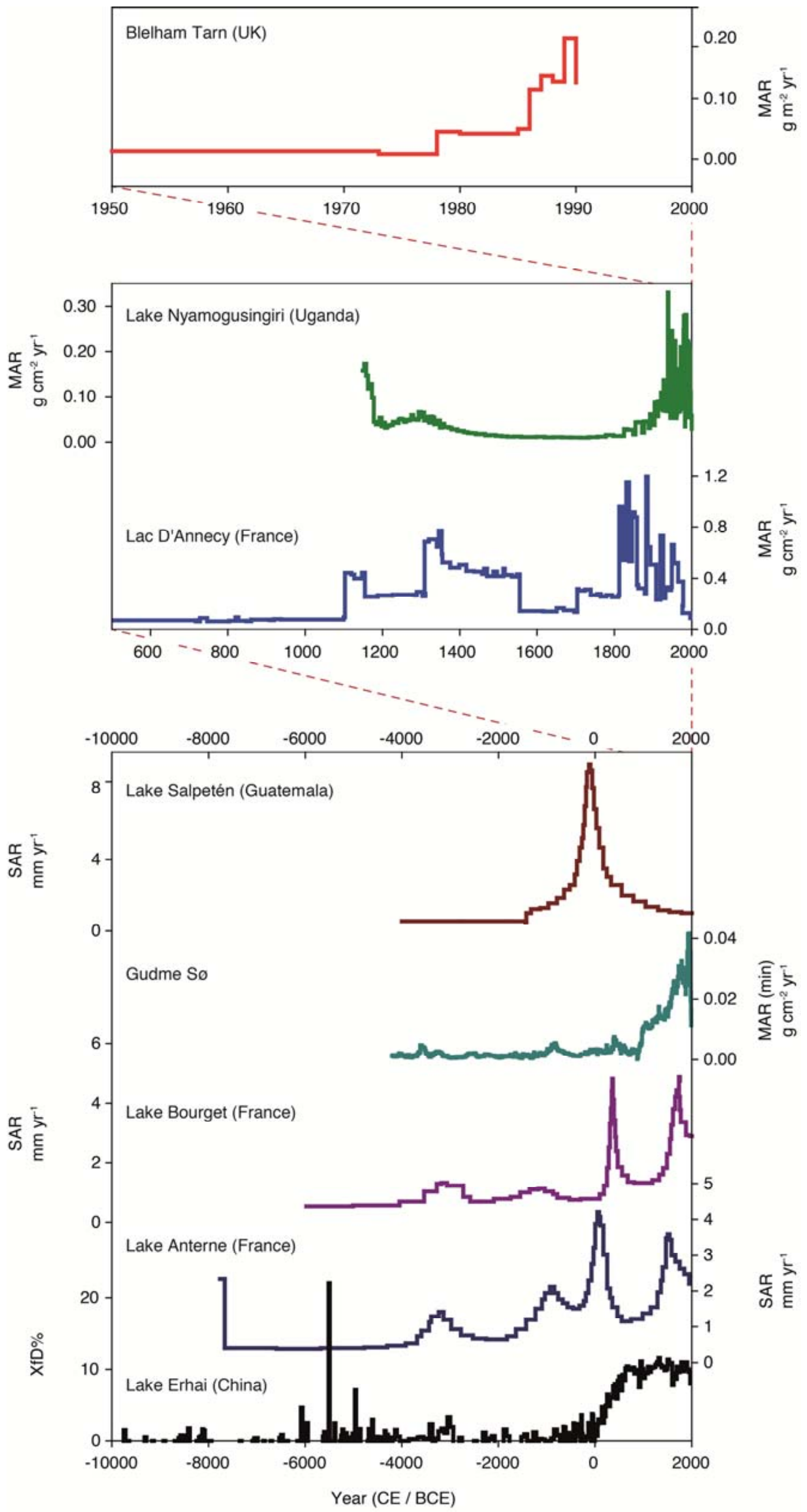


Figure 5: Sediment accumulation rate curves from a series of selected lakes, with a global spread (Lake Erhai[69], Lake Anterne[82], Lake Bourget[83], Gudme Sø[84], Lake Salpetén[85], Lac D'Annecy[71], Lake Nyamogusingiri[78] and Blelham Tarn[86]). In all cases the accumulation rates (MAR) show an increase attributed to human activity. The differences in timescale should be noted, and highlight how human activity has impacted (and intensified) erosion rates during the Holocene.

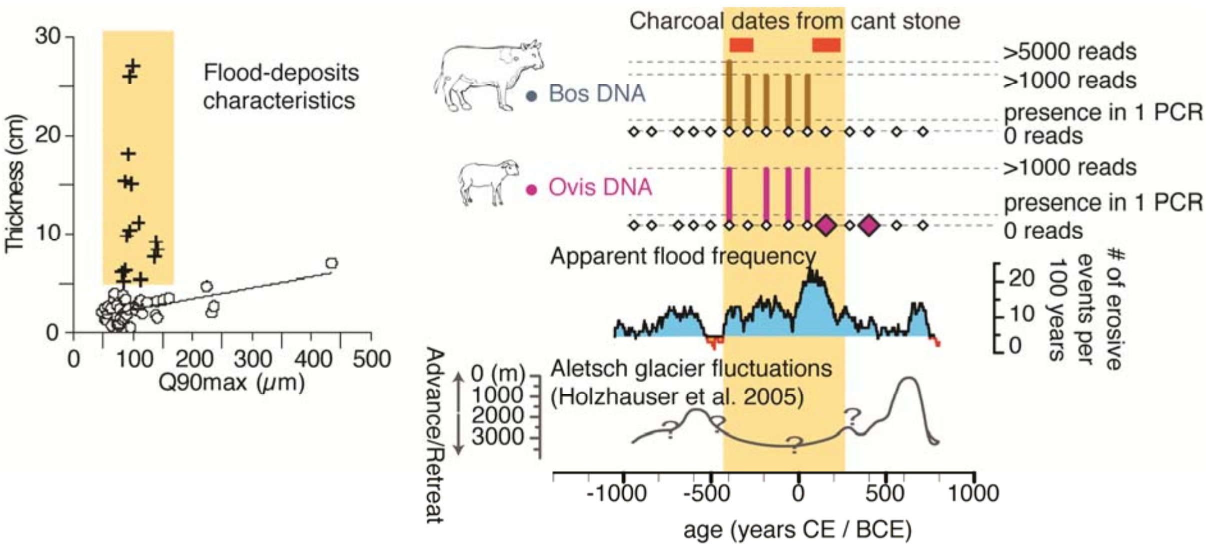


Figure 6: Thickness vs maximum grainsize in Lake Anterne flood-triggered deposits over the last 10,000 years. Black crosses highlight samples from Iron Age-antiquity enhanced erosion period that is marked by drastic rise in thickness (i.e. the amount of solid flow) without any significant rise in grainsize (i.e. the intensity of the flood-triggered stream flow)[80, 81]. The human origin of this disturbance in the erosion-climate relationship is suggested by the presence of a pasturing hut dated the same age close to the lake[79]and the absence of any significant glacier advance in the Alps during this period. The first ever sediment DNA-based reconstruction from the lake suggests the presence of domestic animals, from which pasturing activities are inferred. The sedimentary DNA profile provides an independent line of evidence attesting to the anthropogenic driver of observed changes in the sediment archive[79] (Giguet-Covex et al., 2014). [Redrawn and adapted from Arnaud et al. (2016) and Giguet-Covex et al. (2014)].

Sediment accumulation rates often accelerate through the mid- to late-Holocene in response to anthropogenic pressures[87, 88]. In lowland Guatemalan lakes, large increases in soil erosion and a dramatic sedimentological shift ca. 3000-1000 yr. BP is attributed to the rise of the Mayan civilisation[85, 89] as a result of increased deforestation and agricultural practices[90-92]; such soil erosion has led to the deposition of several metres of 'Mayan clay' in many of these systems[93]. In the north-west European Alps several studies suggest a general rise in erosion rates at the end of the Iron Age and during the early antiquity (c. 400 BCE - 400 CE). Not only was this increase recorded in several lakes with small catchment areas[76, 79, 94], a similar signal was observed in Lake Bourget (which is fed by a 4000 km² catchment[83]), and is interpreted as a signal of regional impact[81]. In tropical South America, the increasing erosion in forests is shown by the elevated silica content in lake sediments. This broadly coincides with the appearance of maize in the pollen record and the increasing human activity in the catchment after 6900 years BP[15]. Records from Frains Lake, Michigan (USA), illustrated the erosional impact of catchment vegetation clearance from 1800 CE[95]. The clearance of catchment woodland caused increases in erosion rates to almost 80-times the pre-settlement rates[95]. Similarly, a notable acceleration in SAR occurred across Europe during the second half of the 20th Century[96] and in lakes within Australia's Murray Darling Basin[97] .

Globally, some lakes contain a signal linked to Neolithic expansion (see Figure 2), but others only preserve later signals relating to more intensive land use during the Bronze or Iron Age, population expansion and agricultural intensification (the Roman occupation, Mediaeval period), as a result of Colonial activity (America and Oceania) or widespread impacts associated with industrialisation[98-100]. In some regions, pre-industrial activity generated the most significant sedimentological changes[82]; elsewhere, 20th Century records exhibit the strongest signal[96]. Differences in the recording of these signals is often related to site-specific nuances, such as lake-catchment ratio[71], lake depth (the shallower the lake, the more responsive to anthropogenic pressures)[70, 88, 101] and the geology and erosive potential of the catchment itself[102].

Carbon burial

Organic carbon (C) accumulates in lake sediments as a result of autochthonous (internal aquatic) and allochthonous (terrestrial) primary production in conjunction with loss processes such as bacterial mineralization which occurs in both the water column and sediments[103]. Similarly, carbon burial rates (reported as g C m^{-2} yr^{-1}) reflect both ecosystem production (aquatic and terrestrial) and mineralization rates. In lake systems that have not been subjected to anthropogenic impact, the carbon burial rate is typically <5 g C m^{-2} yr^{-1} (e.g. undisturbed boreal lakes) [104], compared to c. 100 g C m^{-2} yr^{-1} in culturally-impacted lowland systems[105]. Comparing rates across regions and between lakes is often problematic because of sediment focussing (where sediment is preferentially deposited in the deeper parts of lakes), which can artificially accelerate accumulation, though in many cases this can be accounted for using a correction factor calculated from radiometric dating[106]. The relative amount of terrestrial C stored in lakes is primarily a function of catchment geology and vegetation: sediment in boreal lakes is, for example, predominantly allochthonous, but hydrology and catchment disturbance influence the transfer of terrestrial C (as particulate or dissolved organic carbon (POC and DOC)) and nutrients. Anthropogenic disturbance increases C burial rates (see Figure 7) through deforestation and its effect on erosion and transfer of soil C, but it also increases nutrient loading. The latter will increase in-lake primary production (eutrophication) and hence autochthonous C burial rates increase[105]. However, natural landscape degradation driven by climate change can also be important, often increasing C burial rates during periods of cooling[107]. Lake response to catchment disturbance is, however, mediated by landscape scale factors which influence erosion, storage and transfer rates[106]. Despite these methodological constraints, there is no doubt that C burial rates have increased substantially in lowland lakes with forest clearance and the development of agriculture (Figure 7) but also in remote lakes during the recent past[108] associated with trans-boundary global change processes, such as the atmospheric deposition of reactive nitrogen.

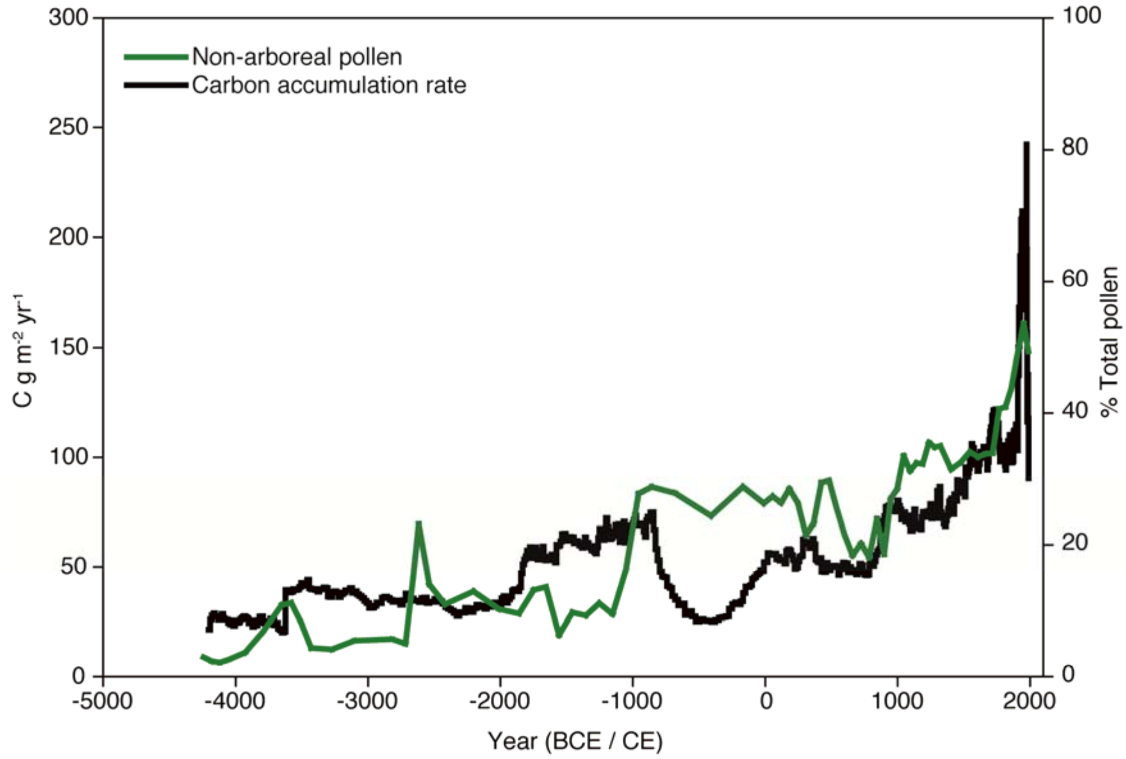


Figure 7: The carbon accumulation rate (CAR) at Gudme Sø (on the island of Fuen, Denmark) showing how rates vary in a cultural landscape. Deforestation started during the Neolithic (c. 2700 BCE) and increased in the mid-Bronze age (c. 1000 BCE)[84]. As well as clearance processes, the C AR reflects a range of other factors, including ecosystem nutrient availability, but most notably variable sediment focussing due to lake infilling. A shallow lake today (c. 0.5 m water depth), the lake would have been nearly 10-m deep in the Bronze Age with more pronounced sediment focussing than today, as a result comparing rates directly can be problematic.

Trace metals in lake sediments

Trace metal contamination (including elements such as arsenic, cadmium, copper, mercury, nickel, lead and zinc) preserved in sediments is perhaps one of the more unequivocal signatures of human impact on lake systems. The exploitation of metal deposits has a long history[109], and there is increasing evidence of the negative impacts these trace metals have on aquatic ecosystems[110-112]. Metal pollution can occur in lake ecosystems as a form of point-source pollution (e.g. from a local mine) with deposited lead and zinc concentrations reaching many thousands of parts per million during industrial mining in the 1800s and 1900s[113-115]. Trace metals may also be released as particulates and are often distributed atmospherically, far beyond the source[116]; contemporary lead enrichment is globally ubiquitous in lake sediments, and >6 times greater than 'background' conditions[117] while two-thirds of current global mercury emissions are from human activity. On millennial timescales, atmospherically transported lead emissions are associated with ore exploitation during the Bronze Age (5000-3500 yr BP), Roman (ca. 2000 yr BP) and Medieval (since ca. 1000 yr BP) periods[116, 118-120]. Earlier evidence (6000-5000 yr BP) of copper production in North

America[121] and the European Alps[122] is attributed to local ore extraction or, in Egypt, to early trading networks[123].

However, the use of trace metal contaminants is not without fault, and their use in teasing apart the anthropogenic contribution is difficult in regions where natural, lithogenic sources dominate the record (e.g. Snowy Mountains, Australia)[124] or where metal supply to lakes is sensitive to variations in hydrological regime[125] and grain size effects (metals preferentially bind to finer grains)[126], which may have either natural or anthropogenic triggers[127]. Periods of climatically-driven weathering may result in higher trace metal concentrations in lake sediments in catchments underlain by metal-rich bedrock[102]. Furthermore, soils are effective sinks for many metals[128] and the susceptibility of the catchment to climatically- or anthropogenically-induced erosion at a later date must be considered. Such problems can be overcome by careful comparison of metal profiles with terrigenous elements (such as rubidium or titanium) and grain size indicators, allowing the quantification of the relative natural and anthropogenic contributions[102].

Hydrological change

Climate-driven hydrological change which alters a lake's water balance, as a result of changes in the ratio of evaporation to precipitation, or the quantity of rainfall received, often manifests as changes in lake level, or lake water salinity, but this is largely dependent on the hydrological and geological setting of the lake. Where surface, or near surface, waters are a significant part of a lake's water budget, any changes to catchment hydrology (e.g. through deforestation) can impact lake hydrology. This has been demonstrated in lake sediment records going back thousands of years. For example, changes in $\delta^{18}O$ and magnesium and strontium (Mg-Sr) records from Lakes Salpetén and Petén Itzá in Guatemala are linked to both natural and anthropogenic changes in catchment vegetation cover, with dense forests causing high evapotranspiration and soil moisture storage, resulting in less water reaching the lake[129]. Mayan civilization altered catchment hydrology through the building of dams, reservoirs and canals. The removal of catchment vegetation for urban development (c. 3000-1700 BP) enhanced soil erosion and altered surface water runoff and infiltration[37] at a time when a drier regional climate was also impacting catchment hydrology.

In Lake Parishan (Iran), excursions in the $\delta^{18}O$ and ostracod records were linked to phases of catchment disturbance (see Figure 8). Intensive periods of agriculture, such as the introduction of the olive (*Olea*), as recorded in a 4000 year pollen record, led to reduced water flow to the lake system, altering its hydrological balance[38]. However, catchment disturbance resulting in vegetation change does not necessarily lead to lake hydrological change. This is especially true in lakes where the hydrology is principally governed by groundwater inflows[13].

Teasing apart the effect of human impact on lake hydrology, as opposed to natural variability, is often difficult beyond the instrumental time period, or period of lake monitoring[130], due to the covariance with one or more potential drivers. The use of multiproxy records can help to tackle this problem, as multiple lines of evidence can narrow down the dominant driver of change, however, in some instances apparent contradictions in the various indicators can still occur[131, 132]. More recently, research is moving towards a 'systems approach', to increase our understanding of particular proxies indicative of hydrological change, or the lake system itself. For example, the development of Proxy

System Models[133] can aid our understanding of the sensitivity of a given lake to climate and/or human-induced hydrological change.

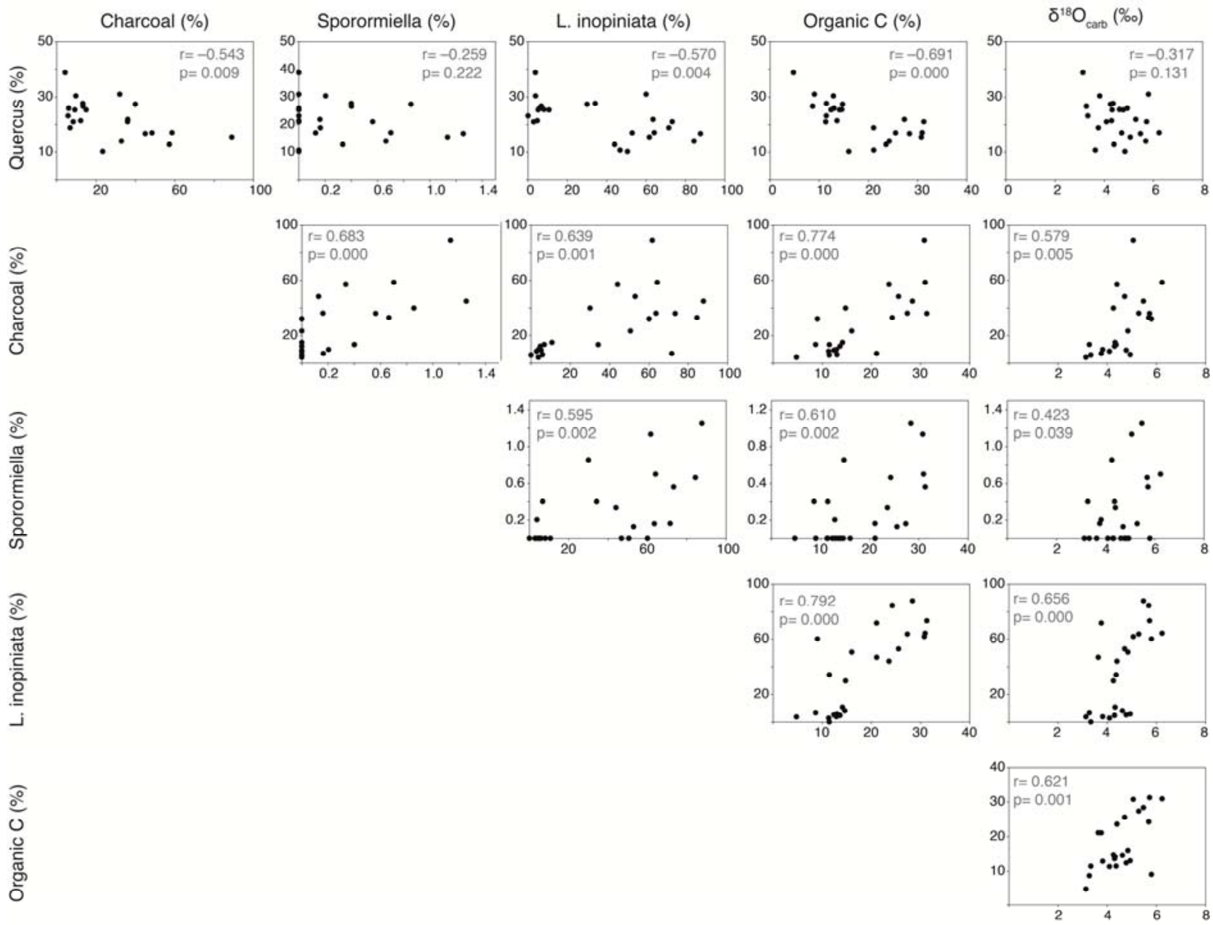


Figure 8: The multiproxy record from Lake Parishan in the Zagros mountains of Iran[38] shows evidence of catchment disturbance from pollen (*Quercus*) and charcoal records, and also evidence of grazing animals at these times from Sporormiella (a fungi associated with animal dung). The ostracod (*Limnocythere inopinata*) and oxygen isotope data ($\delta^{18}O_{carb}$) indicate changes in lake hydrology and the organic content of the sediment (Organic C; sediment composition), some of which correlate with the evidence of catchment disturbance. The water composition (alkalinity: calcium) preferences of the ostracod species suggest that during periods of catchment disturbance groundwater and/or surface water input to the lake was reduced, this in turn led to a decrease in lake level and more positive oxygen isotope ratios. The multiproxy approach narrows the envelope of possible interpretations to explain the data recorded, making anthropogenic disturbance of the catchment the most likely driver of hydrological change for much of this 4000 year record[38]. The scatter plots show data from core depths where all proxies were analysed (there are two samples with no charcoal data). The correlation (r) and significance of the correlation (*p*-value) are also given.

Eutrophication, salinisation and acidification

Eutrophication

Cultural eutrophication of lake waters occurs as a result of human activity within the lake's catchment that increases the nutrient input (principally nitrogen and phosphorus) to the aquatic ecosystem, which can in turn increase algal productivity, change algal community composition and lead to water quality issues and oxygen depletion[134-137]. Many studies have shown that early societies have modified catchments (e.g. removal of vegetation for agricultural purposes) and therefore the water chemistries of lakes in Europe[34, 138, 139], Asia[69, 140], tropical America[85, 89, 135] and North America[135]. Deforestation during Maya civilization was accompanied by increased soil erosion, lacustrine sedimentation and phosphorus loading, and depleted lacustrine productivity up to 400 years BP, suggesting that Mayan urbanisation had impacted the environment[37]. A clear example of recent cultural eutrophication is at Lake Petén Itzá in the lowlands of northern Guatemala. Palaeolimnological investigations from the lake suggest that widespread deforestation occurred as a result of population growth c. 1930 CE. This led to increased sediment accumulation and catchment runoff, leading to an increase in phosphorus loading (and nutrient enrichment) of the lake system. This was not only evidenced through changes in the geochemical record, but also changes in the biotic structure of the ecosystem, with the prevalence of siliceous algae (diatoms) that preferred hyper-eutrophic conditions[141]. Similarly, sediment records from Lake Sauce (western Amazonia) suggest that local agricultural activity (as suggested by the introduction of maize pollen) during the mid- to late-Holocene not only enhanced soil erosion, but also led to an increase in nutrient loading to the lake system, evidenced by changes in the diatom composition[15].

Salinisation

Climate change can have a direct impact on the salinity of lake waters simply by contributing more, or less, freshwater through rainfall, which acts to dilute, or concentrate, the lake's salinity. It is on this principle that closed (e.g. crater) lakes are often the focus of palaeolimnological studies directed at reconstructing water balance over time[142]. Whilst long-term changes in effective rainfall will affect all lakes in a given region, the effect of this on the lake ecosystem is often subdued on account of catchment processes. Direct hydrological change by humans, however, has had substantial impacts on aquatic systems through salinisation. The use of water for irrigation, and the clearance of vegetation from groundwater recharge zones, has together elevated water tables that have brought salts towards the surface[143]. Furthermore, the abstraction of water for human use has reduced freshwater inflows to lakes increasing their salinity, a problem that is particularly acute in coastal lakes systems where the freshwater inputs acts as balance to the salt brought in as part of the tidal prism[144].

Acidification

The acidification of lake waters acts as one of the classic applications of palaeolimnology to understanding human impact on lake ecosystems. During the 1970s many lakes, remote from centres of human population (in Canada and Sweden), began to exhibit signs of eutrophication. Similarly, changes were observed in a number of Scottish lochs. Palaeolimnological evidence (specifically diatom analysis) suggested that acidification in the lochs had increased since 1850 CE[145], but was unable to provide a causal mechanism. Additional multiproxy studies employing pollen[146] and heavy metal analysis[147] helped to determine cause and effect. A combination of pollen and diatom analysis from the Round Loch of Glenhead showed that pH (as inferred from the diatoms) had changed in conjunction with the development of peat with in the catchment during the mid-Holocene. However, these changes were very small, and often led to an increase in pH due to the leaching of mineral soils by more acidic soil water from the developing organic land cover that increased the alkalinity of the lake water. Furthermore, the inferred pH changes were minimal compared to the acidification of the lake post-1850 CE and it was unlikely that soil acidification alone could explain the shift. A study of heavy metals at nearby Loch Enoch showed that increases in lead, zinc and copper concentrations were concomitant with diatom-inferred lake acidification. The source of these contaminants was not the immediate lake catchment, and identical results from lake systems across northern Europe attested to an atmospheric source of pollution; in this case an increase in deposition of toxic particles from the atmosphere as a result of industrialisation[147].

Species introductions and extirpations

The movement of people around the world has led to the accidental, and often deliberate, introduction of non-native species to many lakes and their catchments. Such introductions often lead to unexpected and negative effects on agriculture, industry and human health, as well as altering the function and structure of terrestrial and aquatic food-webs, especially as introduced species pose a threat to native ecosystems and their biodiversity[148]. A large-scale example of this is the case of the Laurentian Great Lakes (North America), where human modification of the landscape, including the construction of the Erie Canal and the St-Lawrence Seaway, have played a major role in facilitating biological invasions into the aquatic ecosystem[40]. Coupled with climate and land-use change, eutrophication and pollution, species introductions constitute a major threat to the ecological integrity of lake ecosystems and global biodiversity.

A palaeolimnological approach can be used to determine the timing and extent of biological introductions in lakes and their catchments. For example, plant macrofossils from introduced macrophytes are often preserved in lake sediments. The analysis of additional groups of fossil organisms (such as diatoms, zooplankton and chironomids) can provide detail of the response of the aquatic system (for example due to an altered food-web structure or changes in the nature and amount of available habitat[149, 150]), as a result of such introductions[151, 152]. The recent development of sedimentary DNA analysis is also becoming a powerful tool in the assessing the timing of species introductions, and extinctions, in lakes and their catchments. For example, sedimentary DNA has been used to show that the yellow perch, an assumed invasive species in the lakes of Northern New York State (USA), has actually been present in the systems for over 2000 years[153]. Such discoveries can therefore have important ramifications for the conservation status of many species.

CLIMATE vs PEOPLE: DISENTANGLING THE DRIVERS

Given the impacts of climate and anthropogenic impacts on lake ecosystems are often confounding, and can manifest in similar ways for a given proxy or proxies, one of the challenges facing palaeolimnologists is the ability to determine and separate the relative contributions of climate vs non-climate drivers to lake system responses recorded in the sediment.

Numerical methods

There are increasing number of studies, applying advanced and novel statistical techniques to tease apart the confounding factors as recorded in sediment cores[154]. Methods such as variance partitioning[155] are commonly used to apportion drivers of change. This approach, to some extent, allows the differentiation in the relative magnitude of the drivers influencing the palaeolimnological record. However, the technique is often applied to an entire core sequence, and as such does not account for a change in the dominant drivers through time, nor shifts in their relative magnitude[156]. The ability to provide such a timeseries of the contribution of the various drivers, as opposed to a single, overall percentage contribution, is advantageous as it provides insights into fluctuating drivers through time[157].

To address some of the issues associated with the blanket application of variance partitioning, two studies (from Denmark[34] and Uganda[78]) have attempted to develop the variance partitioning approach by separating out records of drivers (e.g. pollen[34], sediment accumulation rates[78]) from aquatic response (i.e. diatoms), and applying variance partitioning to a subset of the timeseries[34], each subset representing periods of 'distinct change' in the sediment record[34]. This approach was designed to determine the different drivers that had influenced the aquatic ecosystem through time. Whilst this approach does not validate cause and effect, the data were used to reason causes for change (e.g. arguments for changes in water depth, changes in catchment use as a driver of eutrophication), and provided a better insight into the roles of different (anthropogenic) drivers through time. However, a potential issue with these studies is that both lacked a truly independent variable representing the 'climate'. Finding the right 'climate' driver is also challenging, as it is often a single term used to represent a multi-faceted and complex system. For example, climate is not always encapsulated by simple metrics such as mean annual temperature; rather it might be the rate of spring warming that drives the response of lakes in the arctic, or the amount of seasonal rainfall driving change in African lakes. The Ugandan study did use a regional lake level curve interpreted as a response to shifts in effective precipitation[78], but the data were offset, did not match in terms of length of record, and could not account for any potential lags between a change in rainfall, and the response of the ecosystem. Both studies do acknowledge the importance of temporal scale and the use of subsets of data when assessing drivers (see Box 2), and suggest that what might be deemed a dominant driver at 10-year intervals may not hold true when scaled up; the longer the time period, the more or less important particular drivers may become[34, 78].

Another common challenge when using palaeolimnological timeseries data is often the irregularity of sampling in time. Whilst subsamples from core sequences represent an integrated sample from a point in time, despite regular sampling down a core (e.g. at centimetre intervals) does not necessarily mean these samples are spaced equally in time. Shifts in sedimentation rates (often caused by anthropogenic catchment activity) can further exacerbate this problem, and non-regular data pose problems for classical time-series analysis[156]. Alternative analyses, such as flexible additive models, have been proposed in order to overcome troublesome timeseries data[156, 157]. The use of additive models on datasets from Kassjön and Loch Coire Fionnaraich[156] demonstrated that these models allow the effects of co-variates through time to be separated, evaluated and compared. The flexibility in the additive models allows for their application to regular and irregular timeseries (as found in sediment cores).

Additive models can also provide robust results in cases where the palaeolimnological record is complemented by long-term monitoring data. An example from Esthwaite Water (UK) provided a rare opportunity to undertake such analyses, with climate and water quality data extending back to 1945 CE. The use of these data in conjunction with sedimentary diatom records, gave a unique insight into the role of climate and nutrients on a lake ecosystem[44]. In this example, the additive model applied indicated that the contribution of phosphorus during the winter months was the most important factor controlling the diatom assemblages for the entire monitoring period. Whilst air temperature had little effect on the diatom community when nutrient levels were low (prior to 1975 CE), as nutrient availability increased with eutrophication (post 1975 CE) it altered the sensitivity of the lake ecosystem, and climate became an increasingly important driver in regulating the diatom community[44] (though phosphorus still dominated).

Whilst novel techniques offer increasingly powerful methods for teasing apart the drivers of change, there are still problems associated with their use. Much of this lies in the nature of the palaeolimnological data, either with the quality of the data, or often the quantity of the data. Even though species response data are used (which can be many in any given palaeolimnological record), they often have to be reduced to a single variable for analysis (i.e. data from 100 species reduced to a single column of data)[156]. This in itself has an array of associated statistical problems[154], in addition to the loss of potentially useful information inherent in the reduction of multi-dimensional, complex reality to one, or at most a few, vectors. Such models cannot be used as a forecasting tool (e.g. for management purposes), as the models are chosen to fit the observed data, and cannot be constrained beyond this[156]. However, these issues are by no means restrictive in their power or use in palaeolimnology, and offer some of the most robust methods available to investigate the causes of change in lake ecosystems[154, 156].

Landscape-scale analyses

Climate variability and human impacts are external drivers of lake dynamics, yet not all lakes respond to external forcing in a similar way, and individual lakes filter and alter these signals in different ways as a result of internal dynamics and resilience[158] (see Figure 9). This can make the identification of drivers of change difficult to quantify, particularly if using a palaeolimnological record from a single lake[78] or generic model. Comparing different lake basins within the same region ('landscape-scale experiments') is one method which can overcome the problems of a single lake approach[159]. In areas remote from human disturbance, such as SW Greenland, it can be assumed that the dominant drivers of long-term (Holocene) change in lakes are ontogeny (lake and catchment development through time) and climate. Examination of patterns from these and other relatively undisturbed Arctic sites does raise questions surrounding the notion of 'reference' conditions, as many of these sensitive lakes demonstrate major shifts over millennial and centennial timescales[160,

[161]. Saline lakes in the region are more sensitive to climate forcing (precipitation: evaporation), with lake levels lowering by >10 m occurring when the climate became warmer and drier[162]. Comparisons of similar lakes in SW Greenland suggest that lake water pH declines as lakes age, but that the rate of the decline depends on the climatic conditions and the particular ecological assemblages in the different lakes [163, 164]. Such observations demonstrate three main principles: (1) lakes develop as they age, and this is associated with changes in catchment weathering, soil development and water chemistry[165]; (2) lakes respond to climate forcing in a variety of ways and (3) the rate and nature of the response varies depending on the specific characteristics of the lake. It is also worth noting that there is an interaction effect as factors (1) and (2) can alter the characteristics of the lake (3); i.e. lakes respond differently to climate at different points in their ontogenetic development and the initial driver may induce a different response when coupled with a second. This idea also underlies multiple stressors and explains why unexpected ecosystem responses sometimes result from multiple stressors. The eutrophication examples in the English Lake District demonstrate this idea very clearly[44] where lakes appear to become more sensitive to climate forcing following eutrophication[44, 166, 167].

In lake districts with limited human impact it is theoretically possible to use quite simple analyses such as synchrony analysis to disentangle the drivers[168]. This analysis assumes that because lake districts are subject to the same regional climate forcing, measuring the synchrony (or correlation) of "response" variables can provide a measure of how strongly a lake variable is responding directly to climate and ontogeny (and climate-ontogeny interactions); perfect correlations among lakes would indicate that the lake variables are entirely driven by these factors. The role of climate can be investigated by removing ('partialling out') the long-term trend of lake ontogeny. Whilst this is a relatively simple approach, a number of assumptions about the relationships and interactions between 'time' and 'response' have to be made. In more highly disturbed landscapes synchrony analysis has been used to understand the drivers of lake variability, highlighting that regional nutrient pollution can drive long-term increases in algae over the past century[169]. The removal of the long-term trend allows investigation of the shorter-term inter-annual drivers of algal abundance. Understanding these relationships provides scope for extracting meaningful information on climate from highly complicated records.

An alternative approach is the use of paired lakes, where one of these systems is designated as a 'reference' lake, and is assumed not to have been subjected to the stressor under investigation. For example, the pairing of a perennially ice-covered Arctic lake with a nearby lake which had a short ice-free season aided our understanding of lake ecological response to ice cover[170]. Inter-lake comparisons can also be useful in more disturbed landscapes where lakes are subjected to multiple stressors[167] and in separating regional and local, site specific drivers if change[78, 171]. Where regional drivers such as atmospheric pollutants are known to have varied across entire landscapes a reference lake can help to define the timing and possible responses of lakes to background atmospheric pollution to provide context for other changes (e.g. point sources inputs, changes in catchment forestry[172]).

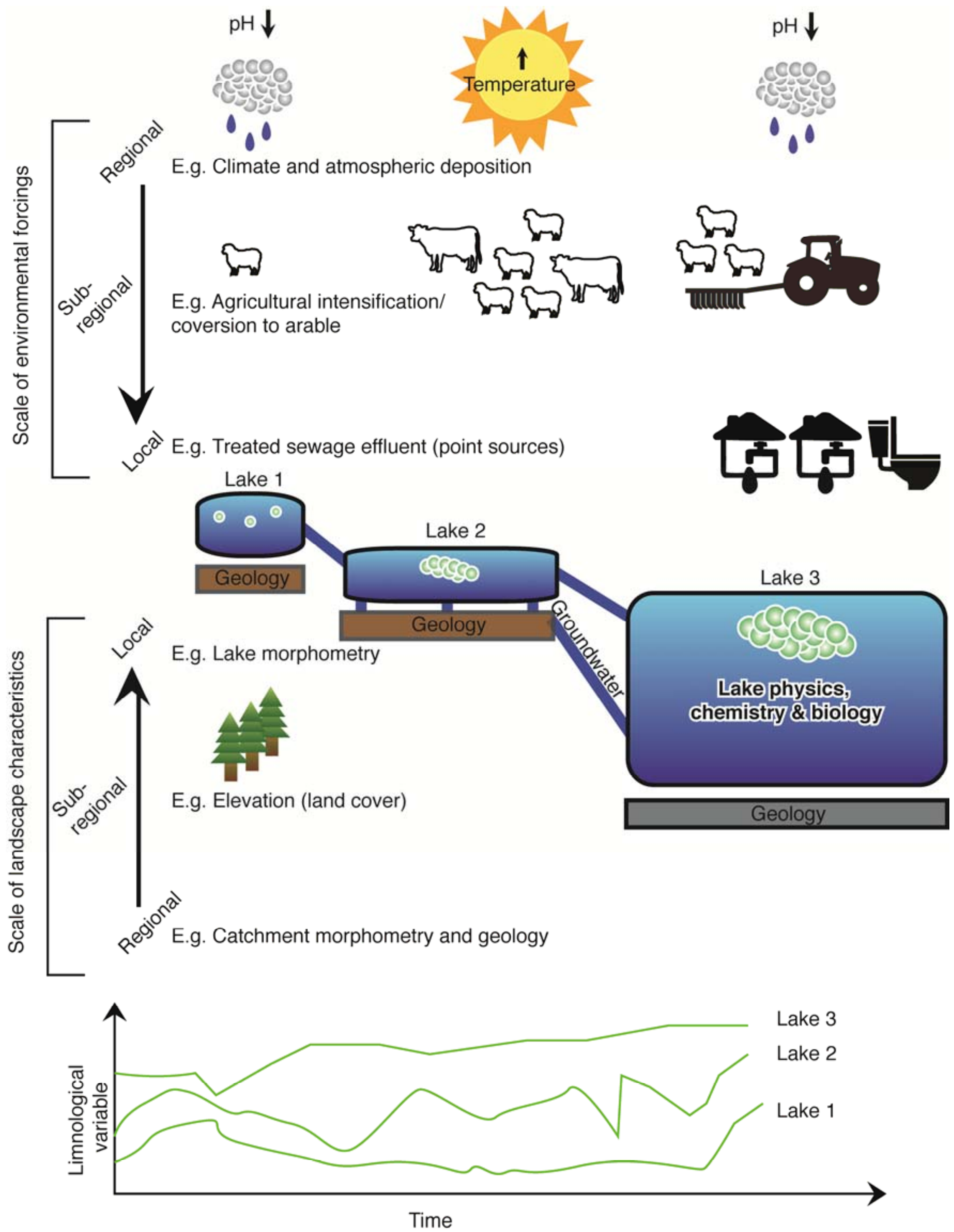


Figure 9: Conceptual diagram of anthropogenically-driven environmental forcings acting over long- to short- temporal scales alongside landscape characteristics (terrestrial, aquatic and subterranean) which shape limnological variables of lakes within a landscape. This serves to highlight that even with identical forcing, lakes can respond in different ways as a result of internal processes and legacy effects[45, 158] (see Figure 3a also). [Redrawn and adapted from Soranno et al. (2009)].

Palaeolimnological study design

The ideal palaeolimnological study is conducted on continuous, undisturbed sediment sequences with reliable chronologies. However for many lake cores, these conditions are not necessarily met, where the cores are exposed to issues related to mixing, sediment focusing (see Box 2) or human disturbance of the record (dredging for example)[173, 174]. A well-designed study, with careful site selection can often negate some of these effects[175]. What is desirable, however, is the use of a multiproxy, multidisciplinary, multi-site approach to analysing sediment records, allowing some of the ambiguity regarding the interpretation of the records to be circumnavigated.

Ideally, when undertaking statistical analyses of sediment cores to apportion the relative contribution of human or climate drivers, the proxy response data would be coupled with a compatible time series of measured or monitored drivers. Ideally this would include an independent measure of climate[166, 176]. Such time series would ensure both driver and response could be analysed together in a quantitative manner[177]. Unfortunately, timeseries relating to drivers are limited only to the time frame during which systems have been recorded; the earliest record of climate comes from a European diary dated to 1399[178], but such records are extremely rare. The availability of documentary evidence differs markedly around the world (but few records extend past 200 years). The timescale on which we need to assess human drivers also depends on the legacy of human impact in the region. For example, in Denmark this could extend to almost 6000 years ago[34]. When looking at timescales and evidence that predates the last century (e.g. ship records and missionary diaries pertaining to weather) quantitative data are seldom available, rather they are qualitative in nature. Despite this, sparse and often *ad hoc* records can provide excellent insights (and independent climate records[179]); notable examples come from missionary diaries from East Africa[180, 181].

In the absence of millennial timeseries data, the most common way of collecting data on the drivers of ecosystem change comes from the sediment cores themselves, but we must be wary of circularity and ensure that all the data used are independent. For example, we may have to be clear about using biological indicators as response data, and not using them as a proxy for the driver. It would not be appropriate to use a proxy indicator to infer a driver of change (e.g. nutrients, pH, or salinity) and also use it as a record of response[177, 182].

A further point to consider is the sensitivity of a lake ecosystem to any given driver. For example, some lakes may appear to be unresponsive to any given change, or some may exhibit an immediate response depending on how the lake system processes the environmental perturbation[158]. In some cases, lakes have been shown to become increasing sensitive to multiple drivers following an initial perturbation[44, 167], especially if the system crosses a threshold[183]. Often the sensitivity of a lake system is a result of its current geographical location. For example the large African rift lakes contain long temporal sequences in their sediment record, reflecting variations in tropical climates on millennial timescales[184] (see Figure 10). Studies suggest that human modification of landscapes through agriculture and metallurgy should be discernible as early as 3000 years ago in parts of East Africa[185-187]. However, because of the strong climatic variability that is characteristic of this region, constantly oscillating between periods of extreme drought and wetter periods, the legacy of human impacts on lake ecosystems is most often lost within the much more pronounced climatic signal[188]. This makes pinpointing initial human disturbances and later historical anthropogenic pressures in

East African lakes challenging. However, some lakes show signs of becoming less sensitive to climatic changes as they become more heavily modified by human activity[78, 189]. However, as with Australia[65], environmental stress brought about by human activities following European colonisation over the past 150 years has been shown to be discernible in lake sediments of this region[190], during what is a relatively stable time period climatically.

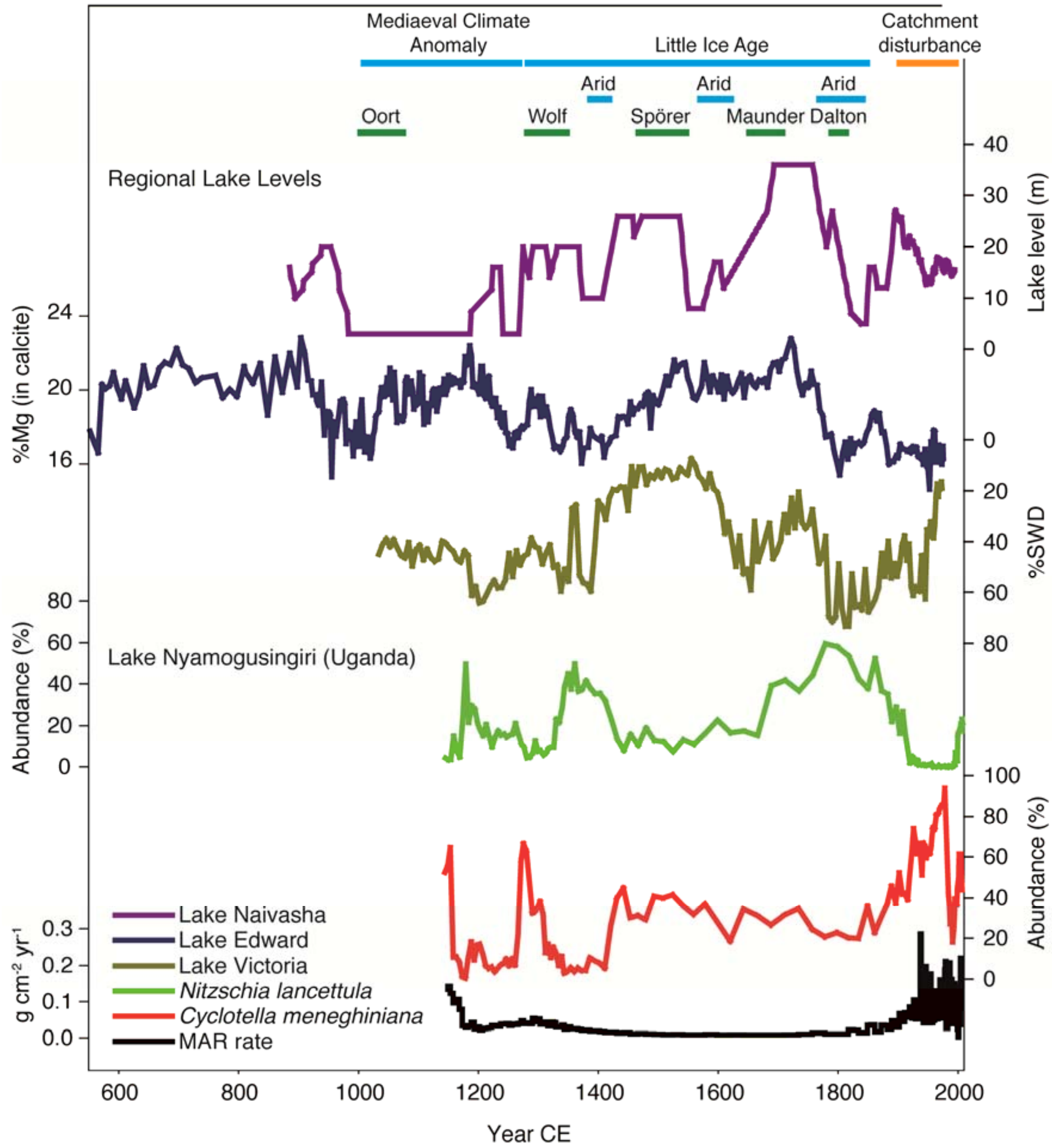


Figure 10: Lake records from across eastern Africa, highlighting the importance of temporal-scaling and the sensitivity of aquatic systems to climatic and anthropogenic drivers. Over long timescales (and often at a lower temporal resolution) many lake systems in eastern Africa record the dominant climate signal of wet vs dry phases (e.g. Lake Naivasha[191], Lake Edward[192] and Lake Victoria[193]; note the inverted y-axis for Lakes Edward and Victoria). In smaller systems, such as Lake Nyamogusingiri (a crater lake in western Uganda)[78], the lake appears to respond to the dominant climate driver over the last 1000 years (indicated by lake level fluctuations inferred from the planktonic diatom *Nitzschia lancettula*). The onset of intensive anthropogenic activity with the lake catchment c. 1900

CE, leads to an increase in sediment loading to the lake system (increase in MAR). This anthropogenic impact decouples the lake response from the climate system, and the lake records an increase in turbidity and nutrient enrichment (inferred from *Cyclotella meneghiniana*)[78].

CONCLUSION

Aquatic ecosystems, globally, are currently under threat from both climatic and anthropogenic forcing of the environment. Lake sediments are an important archive of how these drivers of change have altered in time and the impact that these changes have had on lake ecosystems. Given the limited spatial and temporal extent of measured changes in lake state, and the fact much of this is done on already impacted systems, palaeolimnology provides a crucial tool to aid management of future freshwater resources.

The need for such work is clear given the complexities of lake systems discussed here, and the numerous potential drives of, and responses to, change. Careful research design and data analysis is needed to allow us to begin to pick apart the complexity of the signals recorded in lake sediments. The more work that is done in this regard on lakes across the global climatic, geomorphological, and anthropogenic impact gradients the better our understanding of the systems will become, and our ability to manage them sustainably and carefully will improve. The benefit of lake sediment archives is that they contain the wealth of data needed to understand the systems, and the ability to use a multi-indicator approach allows some independency when it comes to understanding drivers and response[140, 194]. But even with this data-rich archive differences in lake-catchment ratios, lake depths and catchment stability, amongst others, alter how individual lakes filter and record climatic or anthropogenic change. Each lake and each lake system must continue to be treated on its own merits.

The examples and discussion in this paper highlight the need to acknowledge complexity, to choose sites and proxies carefully to record drivers and responses, and to acknowledge the changing sensitivities of individual lake systems, and differing sensitivities of multiple lakes to the same forcing at different times or in different places. Moving towards more process-orientated approaches for analysis[195] such as the energy-mass flux framework, beyond regression models, improves the flexibility of our interpretation tools and allows more nuanced projections of future lake states.

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FURTHER READING

Readers are directed to the book series *Developments in Palaeoenvironmental Research* (series editor J. P. Smol). Please see: http://www.springer.com/series/5869 for a list of volumes currently available in this series.

The SAGE Handbook of Environmental Change (volumes 1 and 2; edited by J. A. Matthews), would also provide an introduction to the interdisciplinary science of environmental change. Please see: https://uk.sagepub.com/en-gb/eur/the-sage-handbook-of-environmental-change/book235322

For more information related to the use of a palaeolimnological approach to the management of aquatic ecosystems, the reader is directed to the Research Topic 'Using paleolimnology for management and restoration of lakes' in a special issue of *Frontiers in Ecology and Evolution*. Please see: http://journal.frontiersin.org/researchtopic/2935/using-paleolimnology-for-management-and-restoration-of-lakes#articles for a list of all available articles.

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